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SUPERCONDUCTIVE MAGNET SYSTEM, 14-TESLA, 15-CM-BORE

by E. R. Schrader and P. A. Thompson

Prepared by
RADIO CORPORATION OF AMERICA
Harrison, N. J.
for Lewis Research Center

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

This summary report describes the work performed by RCA on NASA Contract NAS3-7101 during the period from March 1965 to February 1967. N. S. Freedman, Manager, Superconductive Products Operations, was responsible for the overall supervision of the contract. E. R. Schrader was the project engineer. C. S. Corcoran, Jr., Space Power Systems Division, NASA-Lewis Research Center, was the Technical Manager with J. C. Laurence, Electromagnetic Propulsion Division, NASA-Lewis Research Center, as Technical Advisor.

SUMMARY

This summary report contains a description of the design and construction of a 14-Tesla (140-kilogauss) electromagnet with a 15-cm bore and using Nb_3Sn ribbon. This superconductive magnet was developed for the NASA Lewis Research Center by RCA, Electronic Components and Devices, Harrison, N. J..

A support system was developed in parallel with magnet design and construction. This system contains a standard research helium Dewar and commercially available power supplies. A control console and interconnecting cables designed by RCA complete the entire magnet system.

The magnet has four electrically separated groups of windings, the power to which can be supplied and controlled individually. This arrangement provides for a wide range of sequential and synchronized control of the electrical modules. Such control is necessary when optimum powering of the magnet is obtained and field produced by the electromagnet is maximized.

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SECTION I

INTRODUCTION

The Lewis Research Center is the NASA organization primarily responsible for the development of space power and propulsion systems. Many advanced systems require magnetic fields that may be supplied best by superconductive magnet systems.

Because of these needs, the NASA Lewis Research Center has supported two contracts with RCA to study the feasibility of large-volume, high-field-strength, superconductive electromagnets.(1) As a result of these studies, the feasibility was demonstrated, and contracts with RCA were entered into to design and develop these magnets.(2)

Design of these magnets was based upon the use of the niobium stannide (Nb_3Sn) superconductive ribbon. This ribbon was developed by RCA and was used successfully to produce the first 10-Tesla magnets with a bore size of approximately 2.5 cm.

Modular construction was used as a result of RCA's discovery of methods to overcome the unstable characteristics of high-current superconductors. These unstable characteristics are encountered when superconductors are wound into magnets. Concurrent with these discoveries, development of superconductive materials for use in specific field regions was completed successfully.

These discoveries led to development of the modular concept of magnet construction for establishing optimum current densities in the windings for specific field locations. At the same time, the concept of powered groups of modules was applied to the magnet design to promote stable operation.

These technological advances culminated in the superconductive magnet system (Figure 1) delivered to the NASA Lewis Research Center and described in

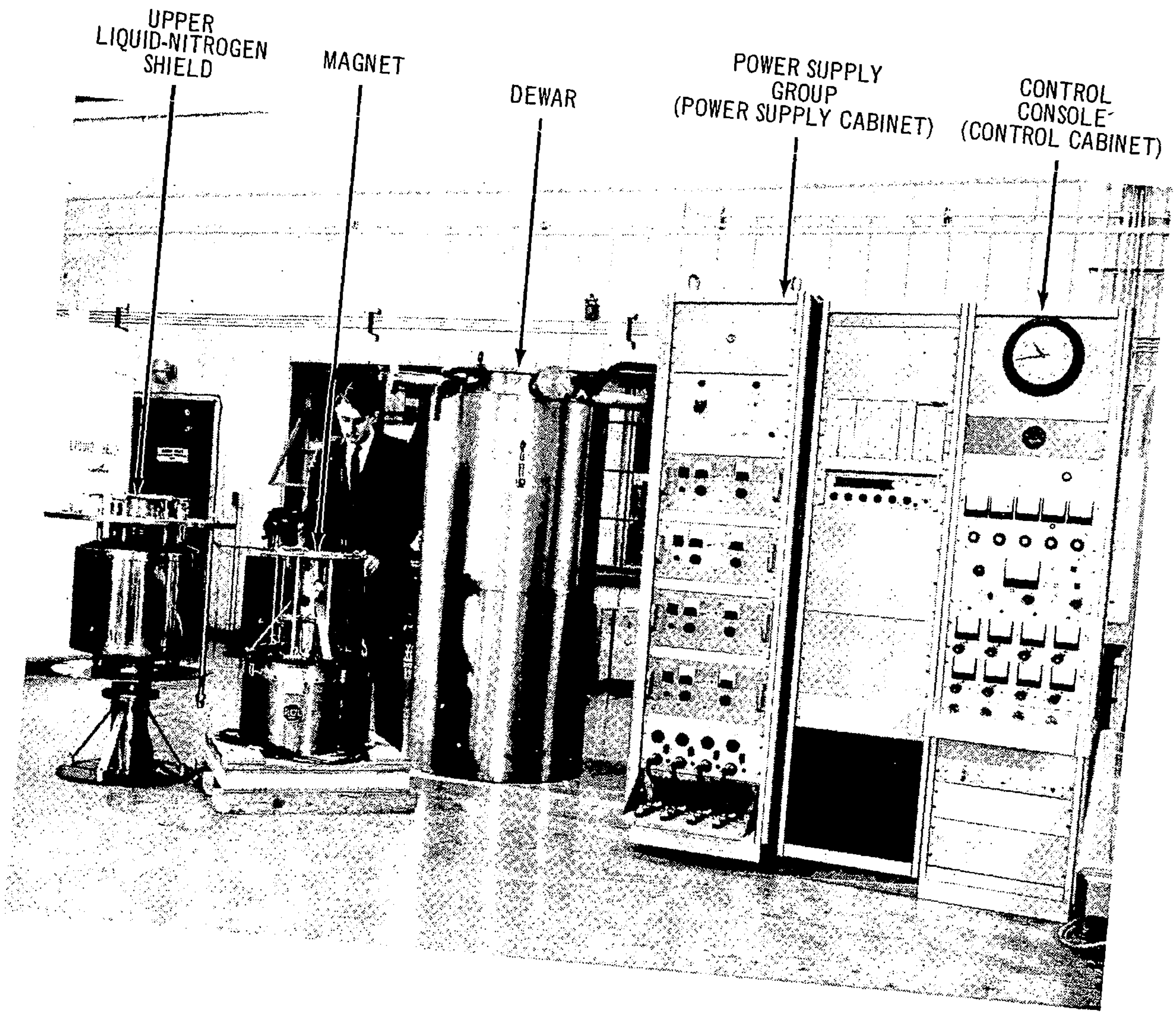

Figure 1. Superconductive Magnet System

detail in subsequent sections of this report. The 14-Tesla (140-kilogauss), 15-cm-bore magnet is shown in Figure 2.

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(1) Contracts NAS 3-2520 and NAS 3-5240.
(2) Contracts NAS 3-7101 and NAS 3-7928.

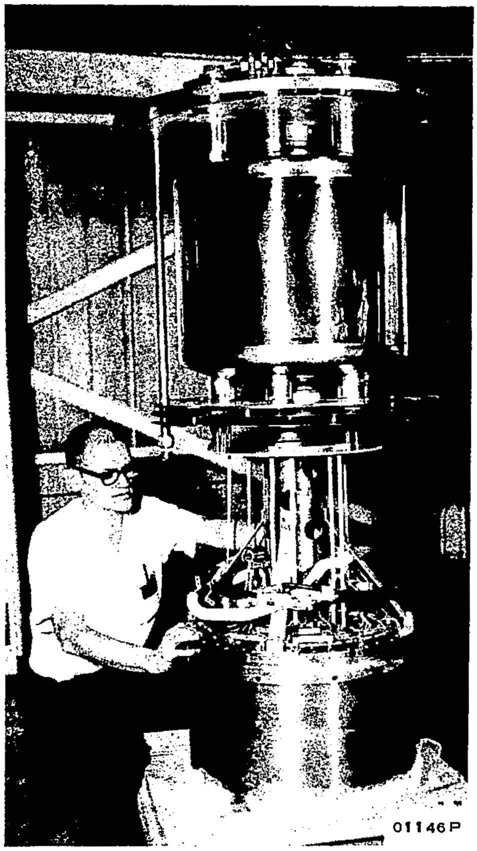

Figure 2. 14-Tesla, 15-Cm Bore, Superconductive Magnet

SECTION II
SYSTEM CONSIDERATIONS

A. BACKGROUND

At the time of initiation of design of the proposed 15-cm-bore superconductive magnet system, only smaller-bore (2.54-cm) and lower-field-intensity (100-kilogauss) magnets had been made successfully. A consideration of primary importance, therefore, was the large amount of energy that was to be stored in the field. This amount of energy was at least two orders of magnitude larger than the amount of energy stored in any existing superconductive magnet.

It was thought, therefore, that release of this energy could be handled easily if change to normalcy could be anticipated and stored energy could be dumped into an external circuit. Tests of smaller coils, however, failed to enable a determination of any single indication of the pending change that could be used to switch the currents to an external circuit. This conclusion meant that the magnet had to be designed to absorb energy internally when a normalcy occurred.

Providing internal strength and best capacity to absorb energy released and forces developed is somewhat contradictory to high current density for producing high field strength. Any diminution of superconductor volume by replacing the windings with energy-absorbing members or load-bearing structural members is a serious problem. Considerable design practice was required to circumvent this reduction. The problem was handled by producing ribbon for particular sections of the magnet with substrate, superconductive deposit, and silver plating suitable for that section of the magnet. This design approach necessitated modular construction of the magnet. The magnet designed first consisted of 22 modular coil forms with 30 electrically distinct windings, which were grouped into four sections. Power could be supplied and controlled individually to the four sections. Separate copper rings were inserted as engery sinks to protect against transitions.

Tests conducted on the magnet have validated the design concepts. Damage did not occur when the magnet was driven normal - either intentional or accidental.

Shorting strips were introduced into the final fabrication of the coil to stabilize the windings and to limit the amount of voltage build-up in the windings. During charging of the magnet, these normal metal conduction paths increase the helium consumption and charging time but provide for much more stable operation. Many sensors were incorporated into the magnet construction to provide for the voltage drop across each module, for field strength within the windings, and for temperature indication and strain gauges. Some of these sensors were retained to provide information relating to charging of the coils, even though the sensors did not provide an indication of impending change of the module from superconduction to normal condition.

B. SYSTEM

The magnet system (Figure 1) consists of four major components: magnet, Dewar, power supply group (power supply cabinet), and control console (control cabinet). The magnet includes the windings, the magnet structure that supports the windings, the magnet case and end plates, the upper terminal board, and the support tube.

The Dewar is a liquid-helium tank with a 71-cm inner diameter. The tank has liquid-nitrogen shielding for the main vessel and a liquid-nitrogen-cooled, removable upper shield. The upper liquid-nitrogen shield is attached to an upper Dewar cover plate, as is the vertical support tube that holds the magnet. Openings are provided in the upper cover plate for liquid-helium transfer-tube and conductor-lead access and for filling and venting the upper nitrogen pot. The Dewar holds approximately 10 liters of liquid helium per 2.54 cm of height inside the chamber (excluding the magnet). The magnet terminal board is approximately 56 cm above the bottom of the Dewar. Taking into account the volume occupied by the magnet, 200 liters of helium is sufficient to cover the magnet.

Liquid-helium transfer can be accomplished either through a transfer tube inserted down the 15-cm-diameter central bore or through the special side port to which is attached a guide tube running down the inside of the helium chamber. The guide tube directs liquid helium from the transfer tube down to the bottom center of the magnet to take maximum advantage of the heat capacity of cold helium gas as it rises past the magnet.

The power supply cabinet contains four power supplies (0 to 8 volts, 100 amperes) and a control-signal section. The magnet is controlled, under normal operation, from the remote control cabinet, which is described in the following paragraph. Circumstances can occur, however, where it is desirable to control the magnet directly from the power supply cabinet (e.g., power supply cabinet is situated closer to the magnet and Dewar than is the control cabinet). Essential controls are available, for convenience, in the control-signal section of the power supply cabinet.

The control cabinet physically is separate from the power supply cabinet, so that the control cabinet can be placed remotely in a control room. By permitting the power supplies to be placed closer to the magnet, the lengths of the heavy power supply current leads (up to eight) can be minimized. The control cabinet provides the functions of magnet control and programming and diagnostics readout. A level indicator indicates the approximate height of liquid helium in the Dewar.

C. SYSTEM CHARACTERISTICS

To take full advantage of the magnetic field-current characteristics of the superconductors, magnet modules are in four sections that can be powered separately. (See Figure 3.) The largest group of modules is the section comprising the low-field portion of the magnet. (Makeup of the sections is explained in Paragraph III.B. These modules are connected in series at the magnet terminal board and are powered by one of the four power supplies. The remaining three power supplies are connected to module groupings that fall into progressively higher-field regions of the magnet. Figure 4 is a block diagram of the magnet system. When the power supplies are in the programmed mode, they are controlled by the set-in program limits, which are compared to remote voltage indications from the sensing leads of the magnet.

The modules, as grouped, provide different central-field values for each section. These values are listed in Table I.

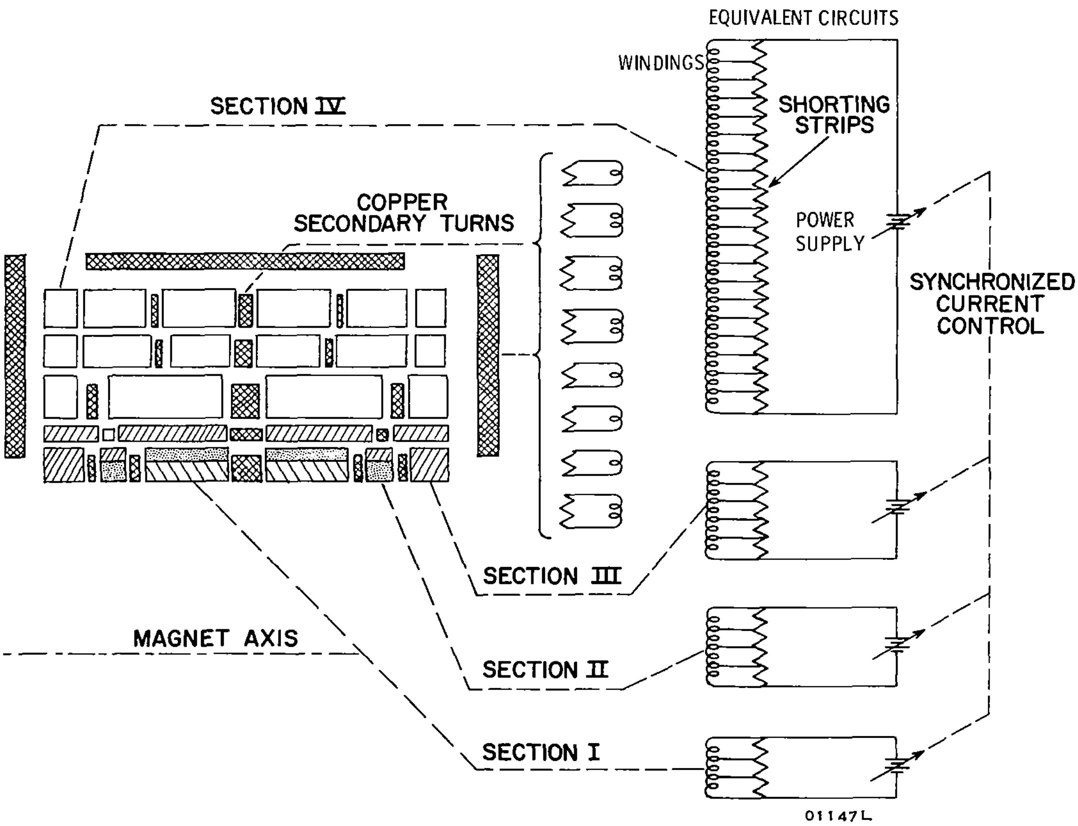

Figure 3. Superconductive Magnet, Schematic Diagram

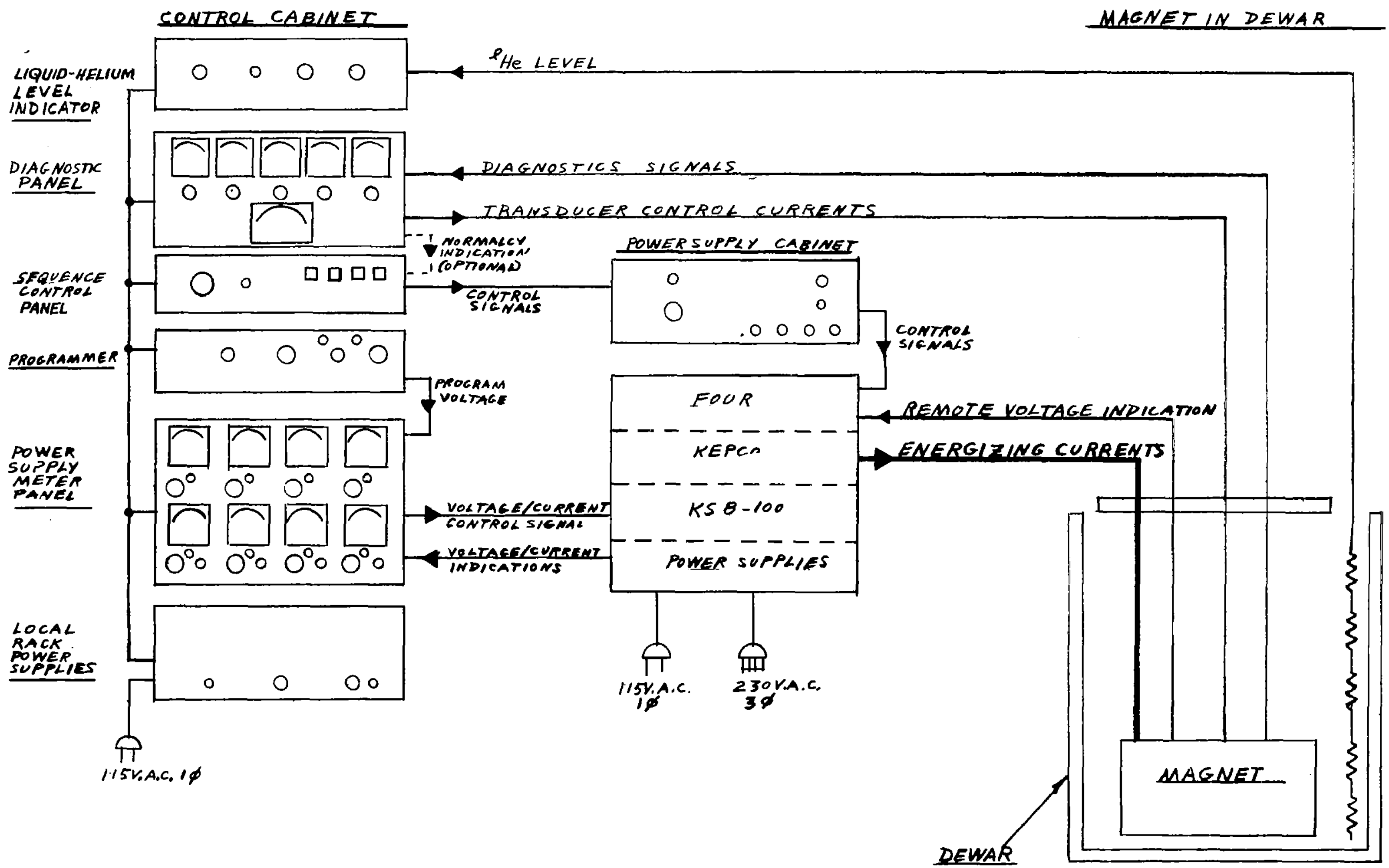

Figure 4. Magnet System, Block Diagram

TABLE I. CENTRAL-FIELD VALUES FOR MODULAR SECTIONS

Section	Central Field per Ampere (Tesla/Ampere x 10^{-4})
I (high-field region)	290
II	241
III	346
IV (low-field region)	1458

It was assumed for the original design that full field would be attained at different final currents for each of these sections. Programming controls are designed to bring all four sections to these different preset currents at the same time. In actual test, there was some hand-manipulation of the relative ratios of the currents.

Voltage and current meters in the control cabinet provide redundant indicators for meters on the power supplies. There also is an indicating lamp to show whether the magnet sections are in the voltage or current control mode. The diagnostic panel provides readouts of magnet and module fields and inductive voltages.

At the time of the writing of this report, the magnet system had undergone 11 tests. Release of energy upon normalcy is well controlled. The magnetic field drops from full to almost zero within 10 to 15 seconds. Automatic introduction of circuits to short the magnet terminals under possible power failure assures that the magnetic field will decay slowly, as governed by the natural time constant of the magnet and shorted lead system. This condition is accomplished as follows: reverse diodes are connected permanently across the load (magnets) terminals; source-power-supply energy is removed by high-speed relays, and the power supply reference voltages are re-programmed to give zero-current output. This approach effectively places a low-resistance short across the terminals of each one of the four magnet sections. Magnet-current decay, therefore, is governed by the time constant of the system, which is determined by the inductance of the magnet and by the resistance of the leads and any normal section of the ribbon. The high magnet inductance and the usually very-low resistances provide a very slow current and, therefore, field decay. For all practical purposes, the magnet retains its field after power source failure, assuring that sudden releases of energy do not occur and cause damage. The stability of the magnet under these perturbations is designed-in and is due to the internal shunting system.

SECTION III

MECHANICAL DESIGN OF MAGNET

A. CALCULATIONS

Methods of calculation and design are discussed in references 1 and 2. Only the more essential points are summarized in this section.

At some range of magnet field and bore diameter, and depending upon the characteristics of the superconductive ribbon or wire, magnet design is relatively complex because of the strong interrelation of parameters. Initial calculations of the ampere-turns required to develop 14 Teslas in a 15-cm bore indicated that high current-density in the windings is necessary. This requirement, in practice, eliminates the use of the more stable superconductive ribbon, which has a low current density ($\approx$5,000 A/cm^2). With large volumes of high-current-density windings, however, current instability occurs, and magnets go normal at lower currents than are expected for smaller magnets. A design operating current is based upon extrapolations from the best available experience. For the 15-cm-bore magnet, therefore, four different current levels originally were chosen between 72 amperes in the lower field regions (as compared with 90 amperes for smaller magnets) and 30 amperes in the highest field region of the magnet.

Solutions of stress equations yield variations in substrate thickness to support the hoop stress in the conductors of the magnet. The current density of the inner windings is lowered, therefore, because of the extra cross-sectional substrate area necessary in the regions of higher stress.

A similar loss of current density occurs because of the axial forces. Somewhere within the windings off the central plane, there are high-radial-field components that cover, in some cases, significant portions of the cross section. Interaction between these radial-field components and the module currents results in large axial forces. Pressure buildup, due to the windings pressing in an axial direction, can be relieved by inserting stress-bearing flanges in the windings in such a way as to transmit the forces from one group of windings, around adjacent windings, to the neutral stress plane. This concept is illustrated in Figure 5 by showing a cross section of windings bearing against a flange. The presence of these stress-bearing flanges, however, decreases the space that could have been used for windings in a simple solenoid, reducing current density.

Other factors, unique to large magnets, account for further losses in current density. One most important factor is that of magnet protection when the device "goes normal." The 15-cm-bore magnet contains 2×10^6 joules of magnetic field energy. If this energy is released uncontrollably as the field suddenly collapses when the magnet goes normal, local overheating and current arcing may occur, which can damage such a magnet.

The 15-cm-bore, 14-Tesla magnet is protected, however, by combined contributions of the following factors:

a. Silver plate on the ribbon

b. Shorting strips of copper foil across each layer of ribbon

c. Interleaving of Mylar-copper-Mylar sheets with copper shorted upon itself to form shorted secondaries that are coupled strongly with the superconductive primary

d. Secondaries made of massive copper-shorted turns: some turns are placed between modules; other turns surround the magnet. The shorted turns placed between modules also occupy volume, reducing space available for windings and resulting in overall reduction of magnet current density.

B. MAGNET CONSTRUCTION

The magnet construction in cross section is shown in Figure 6. Heavy lines indicate outlines of individual modular coil forms. The seemingly irregular placement of these modules is a result of the field geometry causing axial forces that vary among different portions of the magnet. Each one of the 22 modular coil forms (30 electrical modules) has one or more separate pairs of

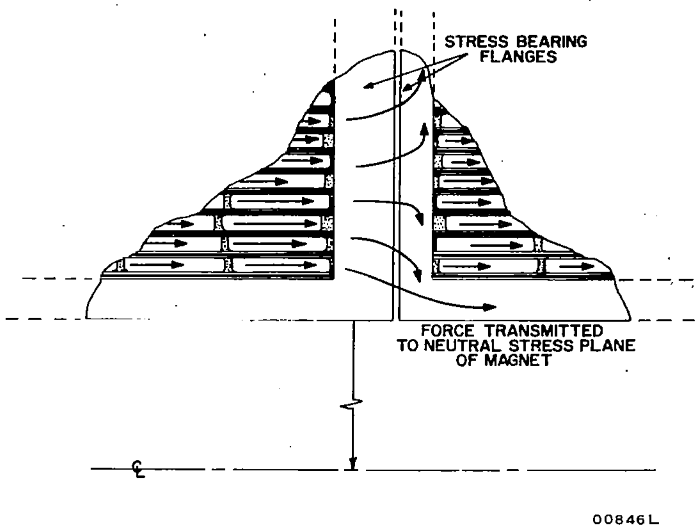

Figure 5. Relief of Axial-Stress Buildup by Force-Bearing Flanges in a Complex Solenoid

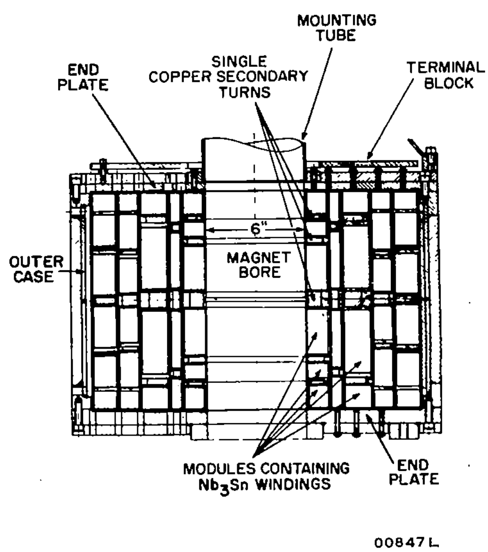

Figure 6. Cross Section of Magnet

current leads and a number of sensing leads going along longitudinal slots to the upper terminal block. All intermodule connections are made at this point. There are single-turn copper secondary windings between certain modules. These windings dampen sudden magnetic field changes and act as energy sinks for induced energy when the magnet goes normal. The copper-stainless steel case and end plates mechanically constrain the modules and act in the same capacity as the single-turn copper secondary windings.

Longitudinal slots, which contain the electrical leads, are passages through which liquid helium can permeate to the modules. Each module, in turn, has similar slots milled radially into the flanges for the same purposes. The magnet, therefore, has a honeycomb of passages that aid in relatively rapid initial cooldown and in cooling while the magnet is in operation.

The actual windings are internal to each modular coil form. These windings are layers of Nb_3Sn ribbon wound over interleaved insulation composed of a Mylar-copper-Mylar "sandwich." The 0.0008-inch-thick copper in this insulating configuration is shorted on itself to form a single-turn secondary, which serves the same purpose as the more massive aforementioned secondary copper turns. The magnet, therefore, is permeated with high-conductivity copper ($\rho_{300^\circ K}/\rho_{4.2^\circ K} = 150$), which is very well coupled inductively with the primary superconductive windings. The copper in the interleaving acts additionally as efficient cooling paths from the module ends.

To avoid large voltage buildups and to serve as a partial means of stabilization, each layer of Nb_3Sn ribbon is shorted at approximately 15-cm intervals around the circumference by thin strips of copper. The cross section of typical winding is shown in Figure 7. Grease is spread on the windings to act as a partial encapsulant.

Because of variations in field and hoop-stress in various sections of the magnet, four types of Nb_3Sn ribbon (Figure 8) were designed for optimization. All ribbons nominally were 0.223 cm wide. Pertinent characteristics of each type of ribbon are listed in Table II and shown in Figure 9. Note that ribbon parameters allow for changes in current-carrying capacity and field range and for change in substrate thickness because of hoop-stress requirements.

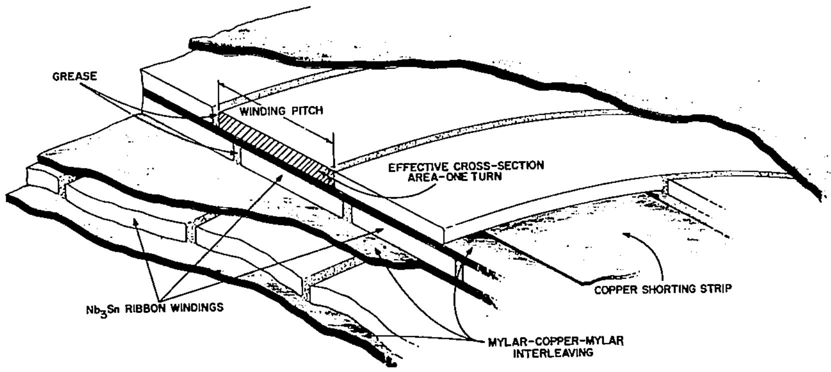

Figure 7. Cross Section of Typical Winding

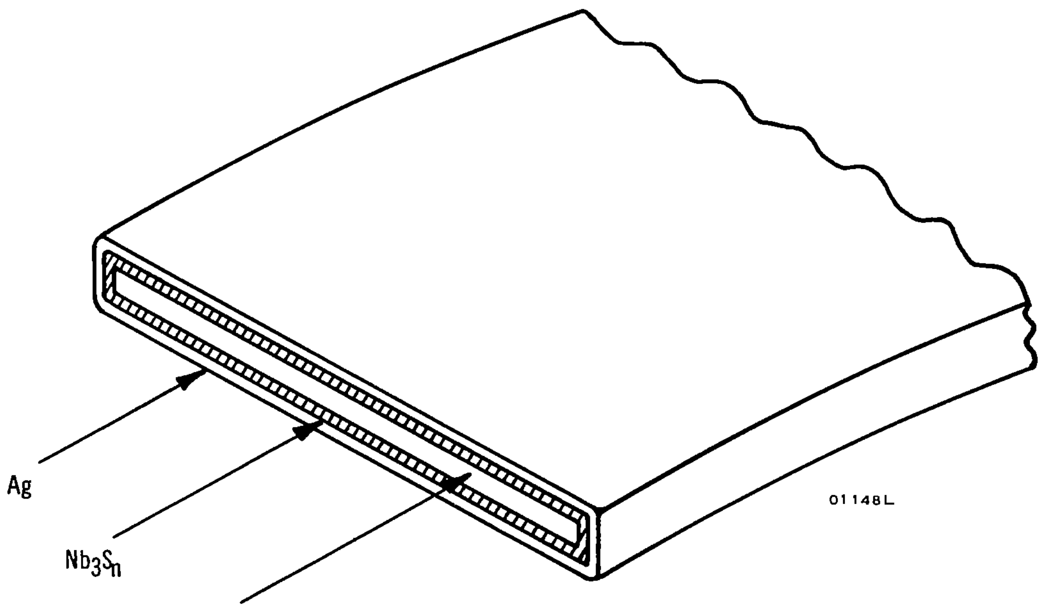

Figure 8. Cross Section of Typical Nb_3S_n Ribbon

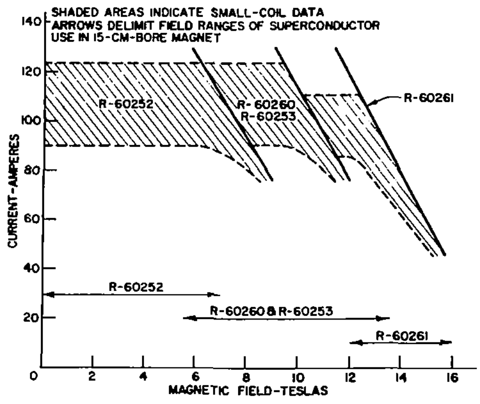

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Figure 9. Field-Current Characteristics

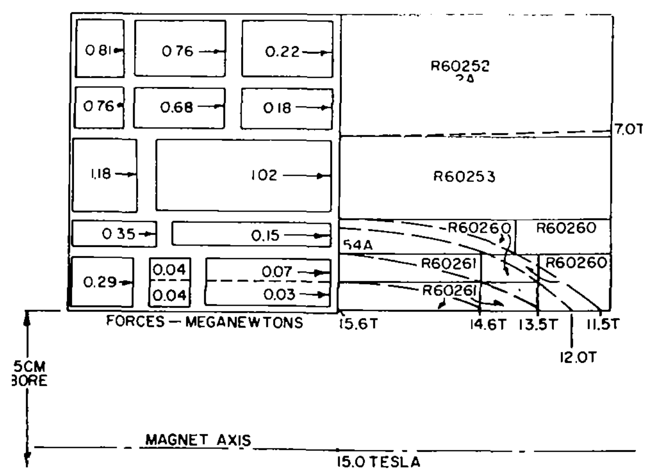

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Figure 10. Computational Design of 15-Cm-Bore, 15-Tesla Magnet

TABLE II. NOMINAL DIMENSIONS OF Nb_3Sn RIBBONS

Ribbon Type	Substrate Thickness (mm)	Nb_3Sn Thickness/Side (mm)	Silver Plating Thickness/Side (mm)	Total Conductor Thickness (mm)
R60252	0.064	0.0064	0.0254	0.124
R60260	0.046	0.0100	0.0254	0.113
R60253	0.064	0.0100	0.0254	0.131
R60261	0.046	0.0128	0.0254	0.119

Placement of ribbons in the magnet is shown in Figure 10, along with approximate locations of constant-field lines and axial forces contributed by the windings of each module. Although the data in Figure 10 are for an earlier 15-Tesla design, the data are almost completely applicable to the existing case. This condition exists because the windings for the 14-Tesla magnet are specified as being operable within the added field of an auxiliary set of magnets that will contribute approximately 1 Tesla more.

Table III contains as-wound data for the magnet, including pertinent information on the contributions of each module to the central field of the entire magnet. Modules are shown grouped into the four sections for connection to the four power supplies. All modules within each section are connected in series. Note that Section IV has, by far, the largest amount of ribbon and turns, and Section I has the least number. The length of ribbon for each module and section is determined by the particular magnetic field range within which the section is optimized. Series connections within each section are made at the upper terminal board. Module groupings for a powered section can be varied from those indicated in Table III by altering the connections. Figure 11 shows the locations of modules of the magnet.

Various probes are buried within the magnet. Each module contains a copper magnetoresistive probe, which is wound noninductively on the center of the inner diameter of each module. Four strain gauges are mounted on module flanges. A main inductive probe is placed in the magnet bore, and smaller (1-millihenry) probes are placed at various locations on the end plates of the magnet.

TABLE III. PARAMETERS OF MODULE WINDINGS

Section	Module	Inner Radius (cm)	Outer Radius (cm)	Axial Displacement from Midplane		Ribbon Length (km)	Ribbon Type	Turns	Layers	H/I at Magnet Centroid (Tesla/A x 10^{-4})	H/I at Magnet Centroid for Each Section (Tesla/A x 10^{-4})
				Inner Edge (cm)	Outer Edge (cm)						
I	A1	7.826	9.525	1.577	8.720	1.709	R60261	3134	112	146.156	290.4
	A1'	7.808	9.530	1.577	8.705	1.684	R60261	3091	107	144.258	
II	A2	9.576	10.907	1.577	8.720	1.522	R60261	2367	85	103.192	241.0
	A2'	9.553	10.892	1.577	8.705	1.592	R60261	2479	88	108.314	
	B1	7.861	9.550	10.241	12.558	0.489	R60261	893	98	14.483	
	B1'	7.861	9.594	10.241	12.558	0.506	R60261	922	101	14.987	
III	B2	9.601	10.960	10.241	12.558	0.516	R60260	799	88	14.723	345.7
	B2'	9.616	10.917	10.241	12.558	0.440	R60260	680	75	12.550	
	C	8.021	10.907	13.805	17.348	1.472	R60260	2472	178	23.212	
	C'	8.072	10.912	13.805	17.323	1.512	R60260	2538	183	23.897	
	D	11.552	12.868	1.796	10.856	2.439	R60260	3180	89	114.400	
	D'	11.552	12.908	1.796	11.067	2.530	R60260	3292	90	117.274	
	E	11.552	12.944	12.522	17.336	1.136	R60260	1476	78	19.624	
	E'	11.567	12.946	12.522	17.336	1.162	R60260	1508	79	20.074	

TABLE III. PARAMETERS OF MODULE WINDINGS (Cont.)

Section	Module	Inner Radius (cm)	Outer Radius (cm)	Axial Displacement from Midplane		Ribbon Length (km)	Ribbon Type	Turns	Layers	H/I at Magnet Centroid (Tesla/A x 10^{-4})	H/I at Magnet Centroid for Each Section (Tesla/A x 10^{-4})
				Inner Edge (cm)	Outer Edge (cm)						
IV	F1	13.564	17.153	1.793	11.750	8.269	R60253	8553	219	266.020	1457.8
	F1'	13.576	17.173	1.793	11.745	8.272	R60253	8565	219	265.703	
	F2	13.559	16.906	13.828	17.338	2.533	R60253	2647	192	37.347	
	F2'	13.559	17.054	13.828	17.348	2.567	R60253	2672	193	37.727	
	G1	18.014	20.627	1.199	6.429	3.932	R60252	3242	157	98.869	
	G1'	18.004	20.604	1.199	6.426	3.917	R60252	3229	157	98.652	
	G2	21.427	24.430	1.247	7.579	6.813	R60252	4722	190	121.919	
	G2'	21.412	24.376	1.247	7.597	6.752	R60252	4699	188	121.137	
	H1	18.004	20.701	7.938	13.868	4.599	R60252	3779	162	81.303	
	H1'	17.998	20.724	7.938	13.876	4.779	R60252	3927	168	84.414	
	H2	17.953	20.213	14.460	17.264	1.979	R60252	1651	150	24.737	
	H2'	18.019	20.607	14.460	17.267	2.045	R60252	1686	153	25.312	
	H3	21.407	24.287	8.570	13.967	5.430	R60252	3695	178	75.013	
	H3'	21.407	24.247	8.570	13.858	5.358	R60252	3731	179	74.317	
	H4	21.397	23.719	14.473	17.252	2.136	R60252	1506	138	22.985	
	H4'	21.392	23.741	14.473	17.282	2.122	R60252	1496	135	22.802	

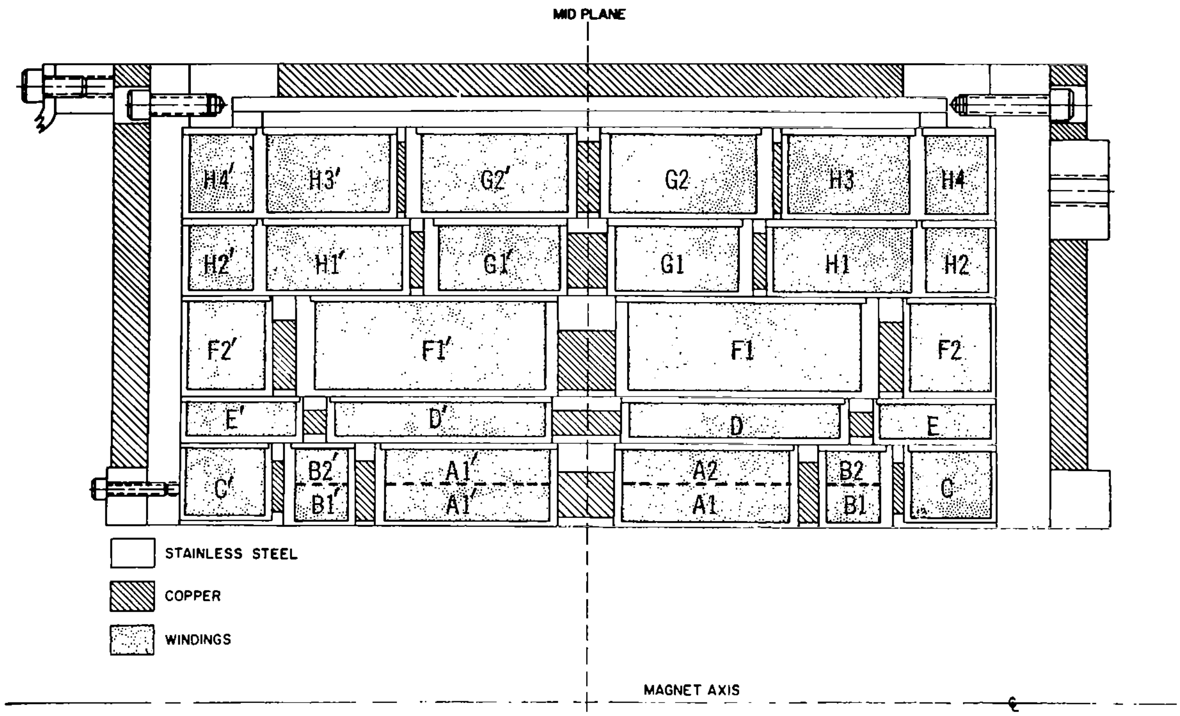


Figure 11. Magnet Cross Section, Showing Module Designations

C. MAGNET SUPPORT-DEWAR

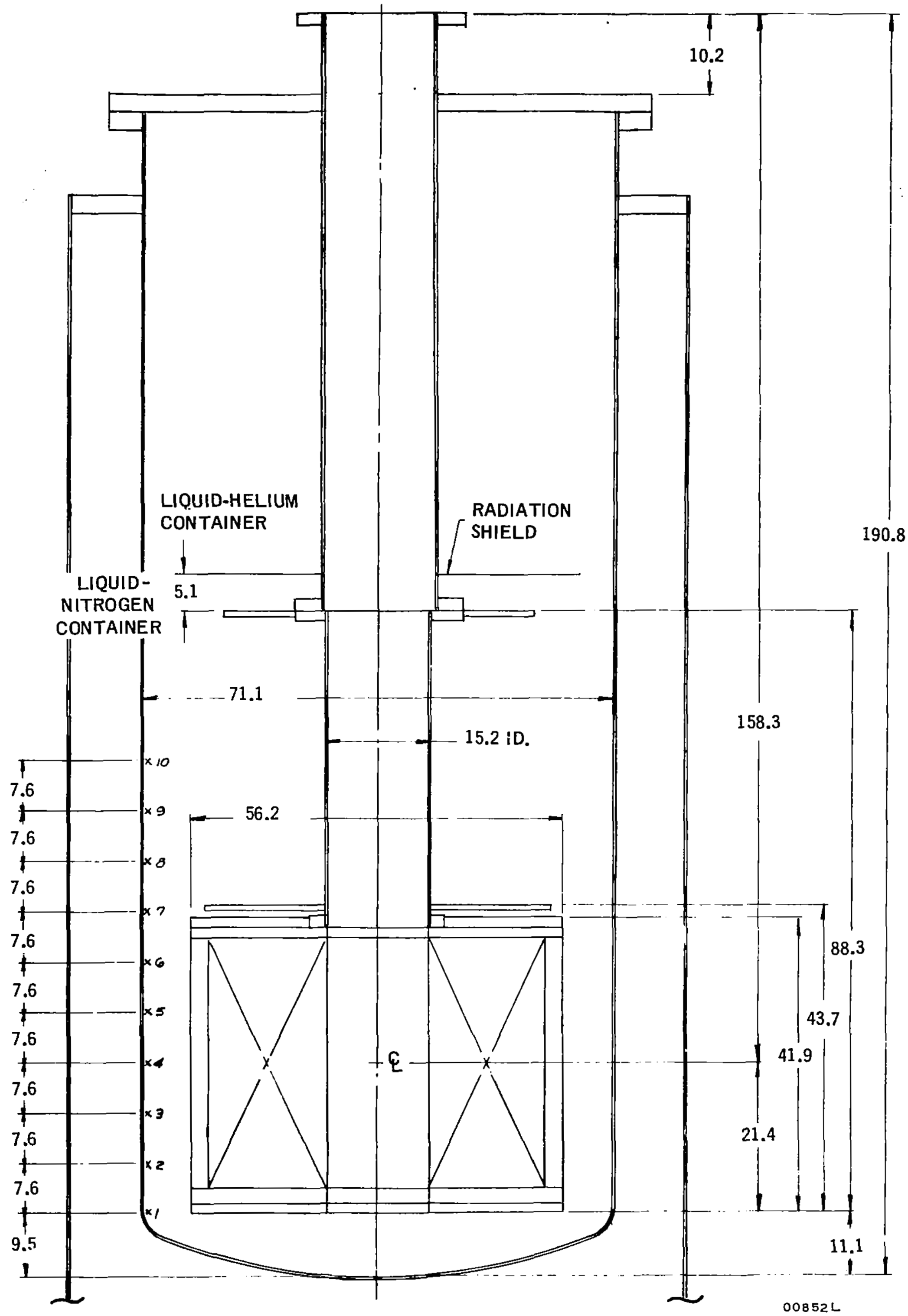
The magnet Dewar is a 71-cm-ID. research type with liquid-nitrogen shielding in both the main unit and in an upper vessel that is attached to the central-bore tube. Figure 12 shows significant dimensions of the Dewar and the magnet supporting means. The upper central-bore tube is attached to the top plate, which, together with the upper nitrogen shield (not shown), forms a single unit. The bottom of the central-bore tube is flanged to mate with a similar flange on the magnet-support tube. With these flanges fastened, the magnet leads are connected to leads that come through openings in the top plate and the upper nitrogen shield. This total configuration permits completion of all lead orientation, and the whole assembly can be lowered into the Dewar as a single unit. A resistance ladder, with resistors placed every 15 cm, is located on the side of the Dewar. These resistors permit readout of the liquid-helium level during magnet operation. Figures 13 and 22 show some of the Dewar details.

D. MAGNET ASSEMBLY

Magnet assembly views are shown in Figures 14 through 22. The magnet is assembled by starting with the bottom plate and progressively stacking the modules of the inner row until the row is complete. The leads from each module are taped lightly along the notches to hold them in place. Module alignment is maintained by the alignment bars, which extend into the bottom plate and fit into axial notches in the stainless-steel module covers.

Each row is built up progressively in this way until the outer row is completed. The outer case then is lowered over the whole module assembly. With alignment rods screwed temporarily into the upper end of the outer case, the top cover plate is lowered onto the assembly. Electrical leads are held within round plastic tubes during this step so that the leads can be located easily within mating holes on the top plate. The tubing serves also to protect the leads against accidental damage.

The terminal block then is lowered over the assembly of leads, and connections are made. After the magnet-support tube is attached, the magnet assembly is ready to be attached to the Dewar support, and connections are made to electrical leads from the Dewar top.



NOTE: ALL DIMENSIONS ARE IN CENTIMETERS

Figure 12. Significant Dimensions of Magnet Supporting Means

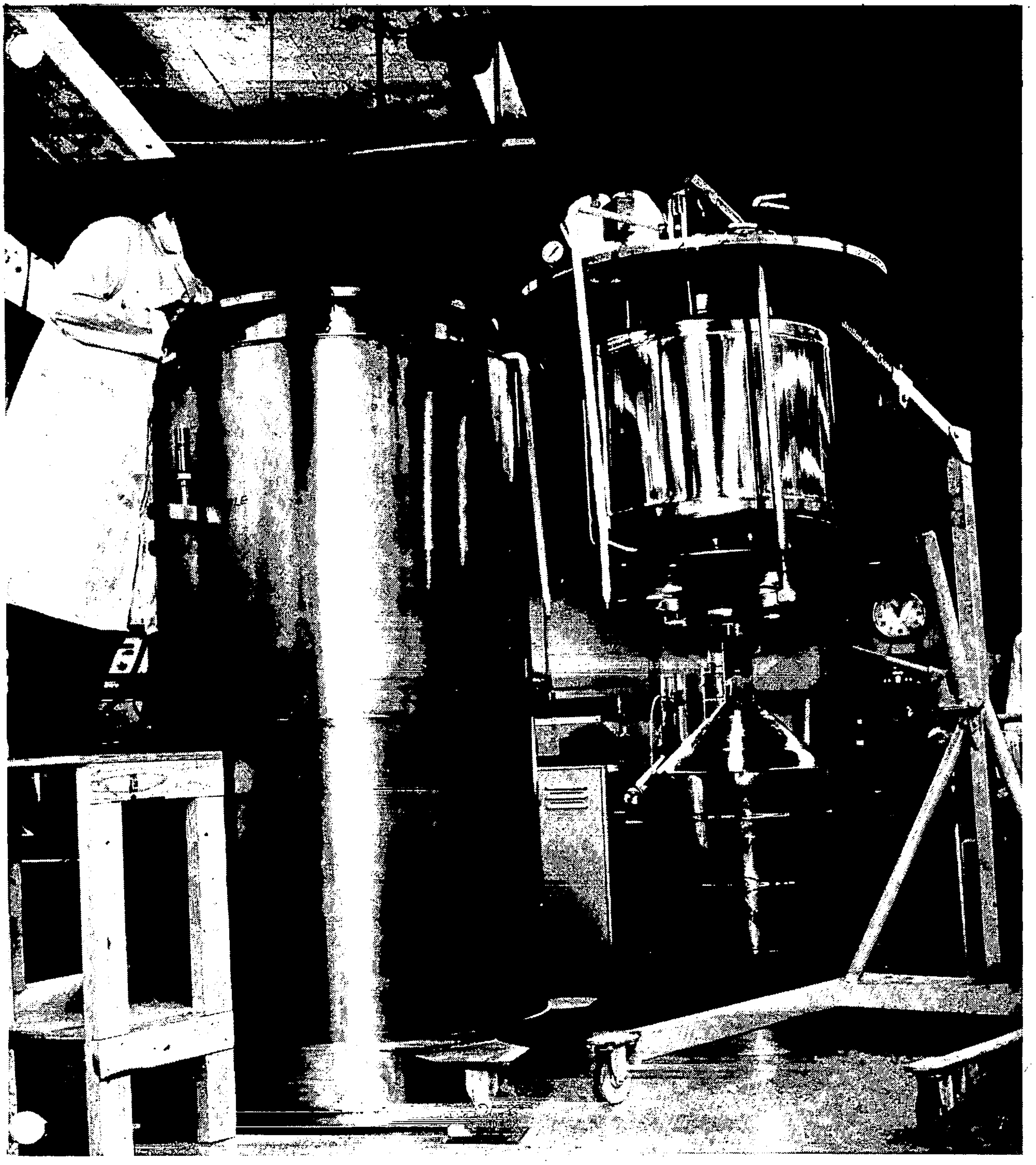


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Figure 13. 71-Cm-ID. Dewar, Showing Main Vessel (Left) and Upper Nitrogen Shield

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Figure 14. Upper Nitrogen Shield during Test of One Row of Modules

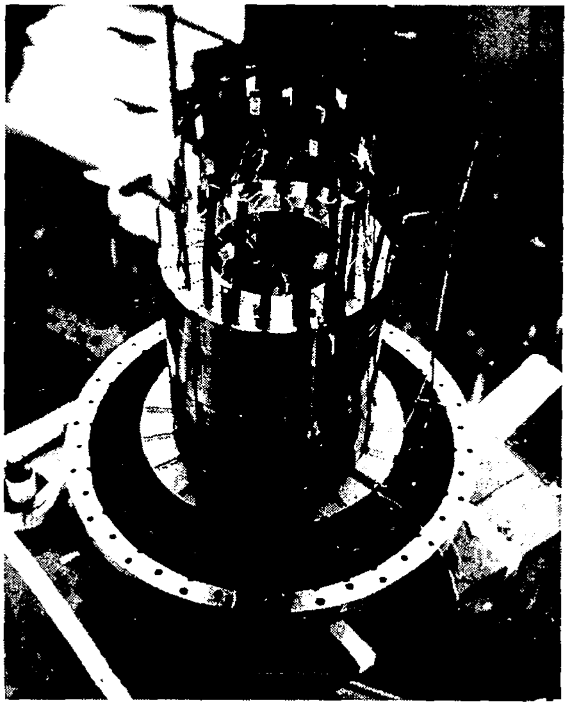

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Figure 15. First Step in Assembling Third Row of Modules

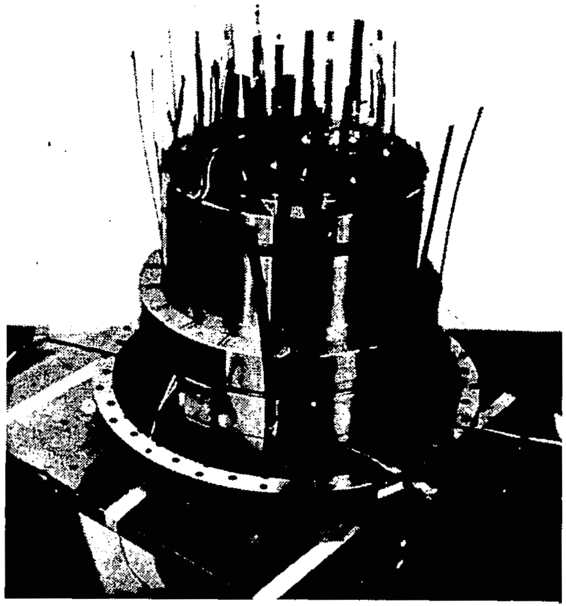

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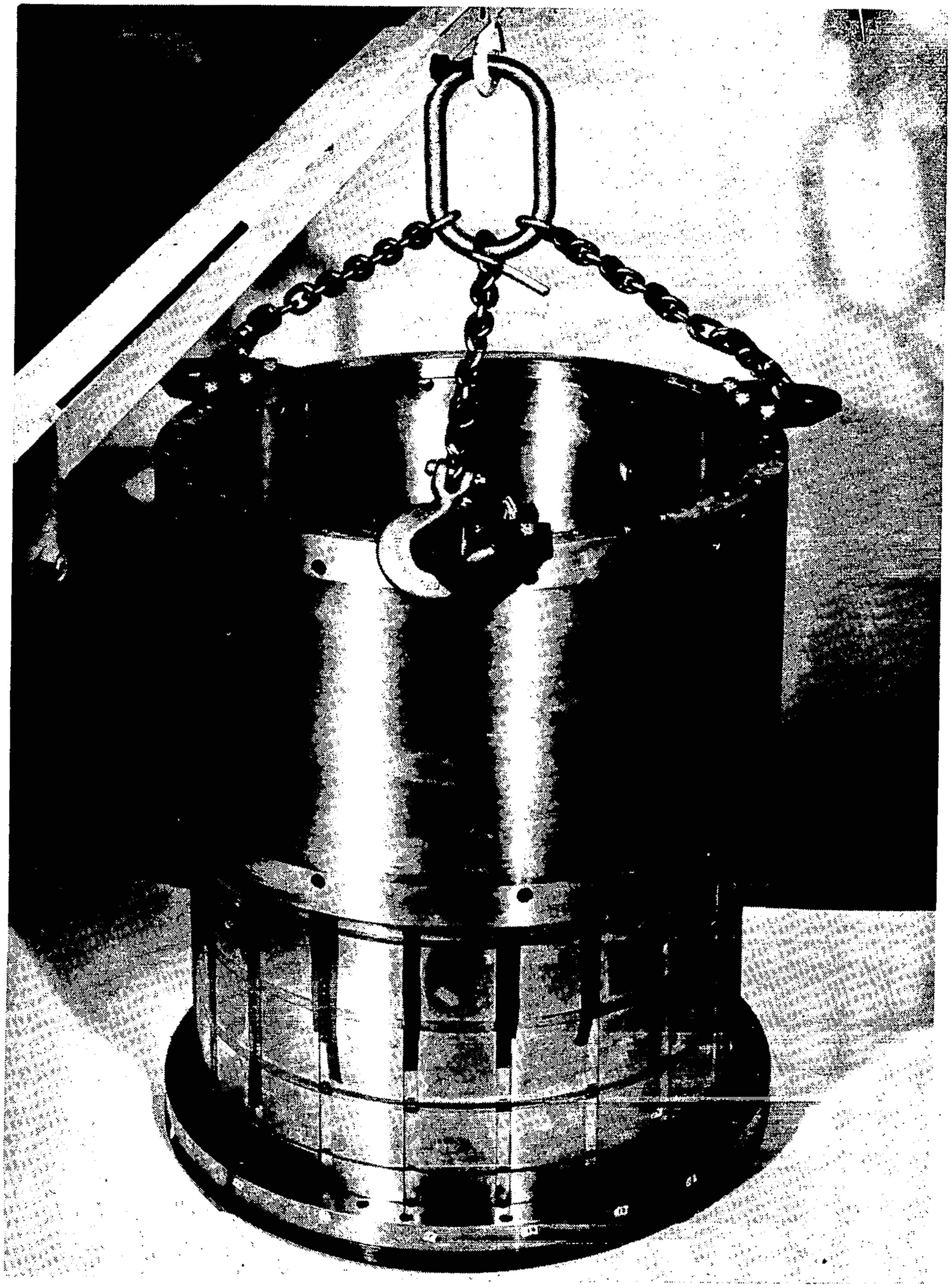
Figure 16. Fourth Row Partially Assembled

00857P

Figure 17. All Five Rows Stacked



00858P

Figure 18. Outer Case Being Lowered over Module Assembly

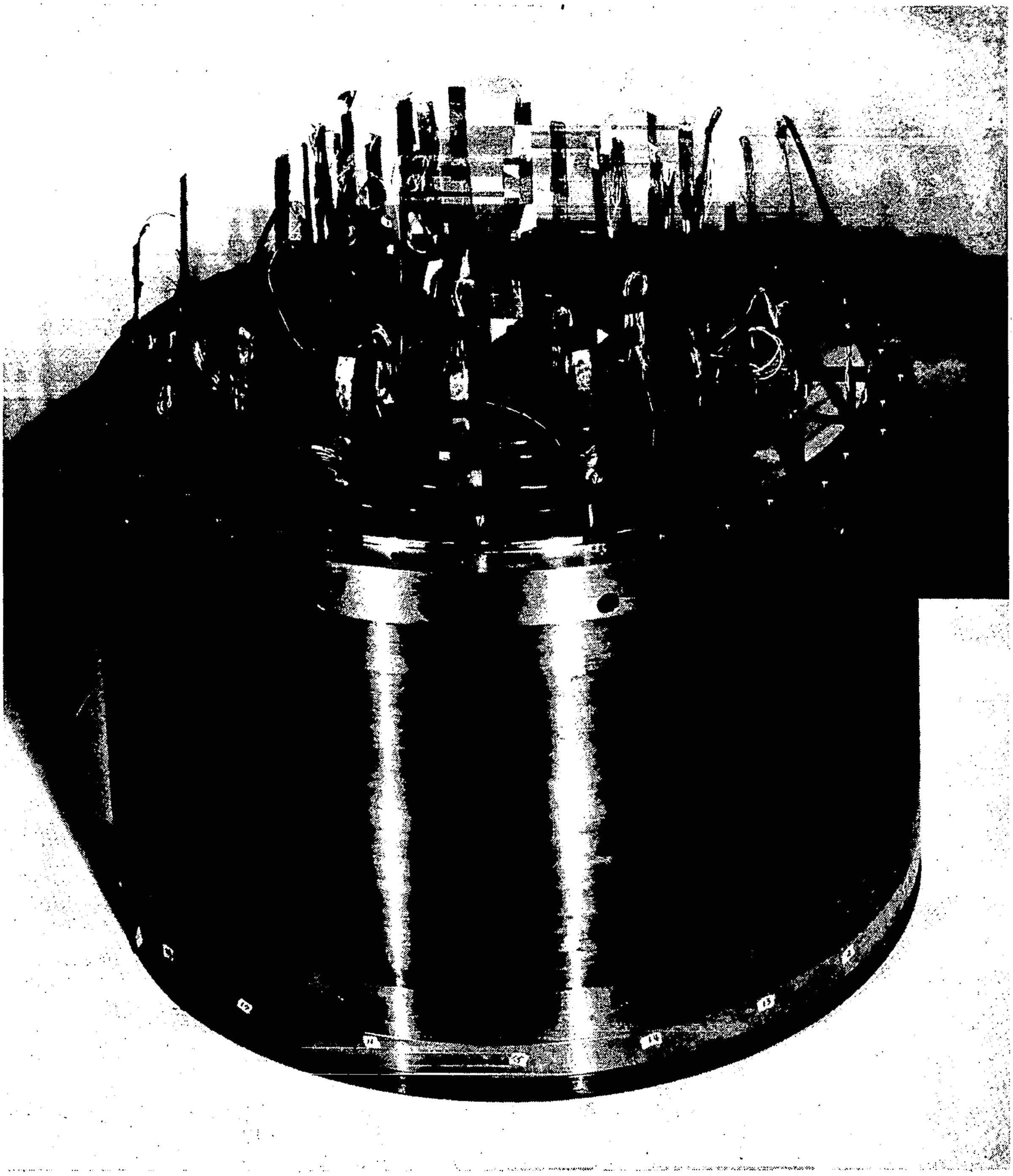
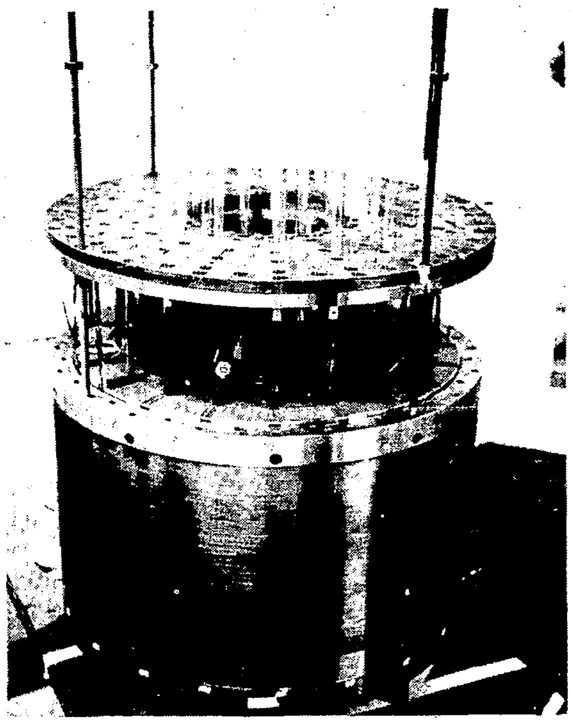

00859P

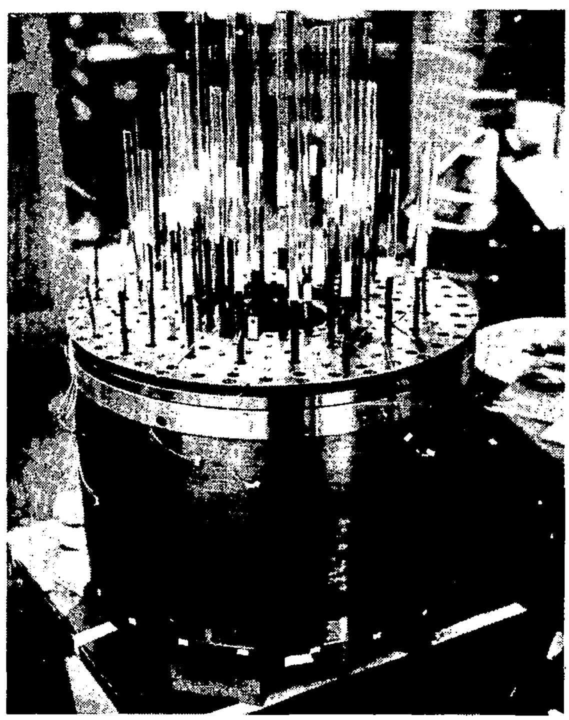
Figure 19. Module and Case Assembly before Installation of Top Plate and Terminal Block



NOTE: PLASTIC TUBES ALINE AND PROTECT LEADS

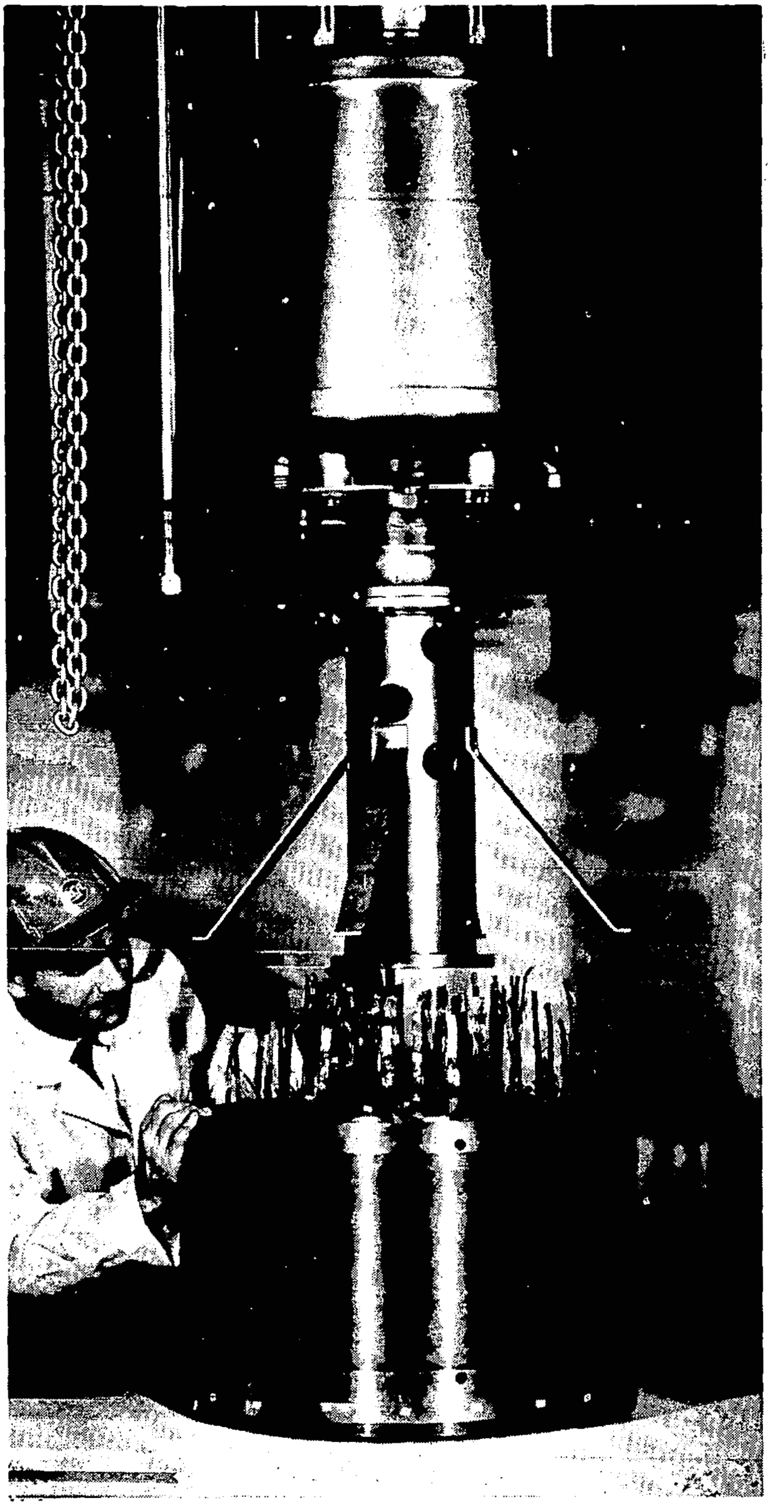
00860P

Figure 20. Top Plate Being Lowered onto Module and Outer Case Assembly



00861P

Figure 21. Top Plate ON, Ready for Bolting to Case



00862P

NOTE: VIEW TAKEN TO ILLUSTRATE PARTS. ACTUALLY, UPPER MAGNET COVER PLATE AND TERMINAL BLOCK ARE ATTACHED AND LEADS CONNECTED BEFORE THIS STEP IS TAKEN IN OVERALL ASSEMBLY

Figure 22. Magnet Support Assembly Being Lowered onto Magnet

SECTION IV

ELECTRICAL SYSTEM

A. MAGNET AND DEWAR

The magnet was built in a modular configuration, with some 90 kilometers of superconductor wound on 22 physically separate formers (modules). The magnetic field of the innermost modules was so high that it was necessary to subdivide physical modules A and B into regions having different types of conductor and current density. The electromagnetic forces of the outermost modules were so great that it was necessary to subdivide the H modules to provide additional mechanical supporting structure. There are, therefore, 30 electrical modules or discrete windings. These 30 modules are grouped into four electrically separate sections, with all modules within each section connected in series. Each one of the four sections can be powered by individual power supplies and can be energized independently.

As a contribution to magnet protection and stability, part of the internal cross section of the magnet is occupied by thick, annular discs of copper. The gentle superconducting-to-normal transitions and electrically quiet operation of the magnet testify to the efficacy of these secondary windings. Specific details of their role, however, still is being studied through advanced circuit analyses.

For providing diagnostics of magnet operation, there are many probes and transducers within individual modules and in the exomodular portion of the magnet. These probes include:

a. Voltage taps at the ends of the windings for each of the 30 electrical modules.

b. Magnetoresistive windings of high-purity copper wire for indicating the azimuthally integrated local magnet field in each of the 22 physical modules.

c. Temperature-sensitive carbon resistors in the flanges of four of the internal modules.

d. A nickel temperature transducer on one of the axial compression rings.

e. Pairs of active and reference strain-gage bridges in the flanges of four modules.

f. A multiturn, inductive pickup coil built into the bore of the magnet on the midplane for measuring the time rate of flux change and for indicating AC deviations therefrom.

g. Six 1-millihenry, air-core, flux-change pickup inductors in different attitudes and at various relative locations about the magnet.

In addition to these probes and transducers, heaters are wound into each of the 22 physical module windings. These heaters are used to induce an artificial normalcy for diagnostics checks or stability studies. There is also a ladder of temperature-sensitive resistors built into the inside wall of the Dewar for remote indication of liquid-helium level.

A bakelite terminal board is affixed to the top of the magnet. All leads from the magnet come through holes in this board and are interconnected by terminals on it. Current leads, made of reinforced copper paralleled by superconductor, are interconnected at the terminal board by special-shape jumpers and heavy copper blocks. Teflon-jacketed signal wires from inside the magnet, necessarily small in order to fit into the flange and axial slots, terminate in solder posts to which are connected the larger Teflon-jacketed wires of the cable extended to the outside of the Dewar. This cable and current leads to the four module sections are tied thermally to the upper liquid-nitrogen pot of the Dewar to reduce their heat load on the liquid helium.

There are demountable contacts, between internal current leads and external welding-type cables to the power supply cabinet, at the top plate of the Dewar. Separate voltage taps from the extremes of the windings of each of the four powered sections are brought in a cable from the magnet to the power supplies for remote voltage sensing. The diagnostics signal leads from the Dewar top to the control cabinet were bunched into four cables, each shielded separately, for convenience. Of these wires, 160 were made into twisted pairs. There are 37 twisted, shielded pairs for low-level signals.

One additional cable connects to the side of the Dewar near the neck. This cable contains the wires from the liquid-helium-level ladder to the remote indicator in the control cabinet.

B. POWER SUPPLY CABINET (FIGURE 23)

Figure 24 is a simplified schematic of the power supply cabinet. The four electrical sections of the magnet are energized by separate power supplies (0 to 8 volts, 100 amperes) (Figure 24). These power supplies can be switched automatically between constant-current and constant-voltage modes of operation. Lamps on the front panel indicate the current mode. In the constant-voltage mode, it is possible, with the aforementioned remote-sensing leads, to control the power supplies by the L(dI/dt) voltage with only a small IR drop (in the order of 10^{-5} ohm) caused by connections between modules.

All points of the control circuits of the power supplies are available at rear terminals, so that remote operation is possible. For standard operation, remote control of both current limit and voltage limit and remote metering are provided at the control cabinet. In addition, the reference for the current-control bridges is obtained from the programmer at the remote location.

For interlocked sequencing and emergency turnoff of the system, a 13-relay, high-speed logic circuit is included in the power supply cabinet. The logic circuit controls the one input contactor for 230 volts AC to the power supplies and the four individual, aircraft-power-type output contactors. Relays in parallel with the output contactors transfer the remote-voltage sensing points from the power supply output terminals (when the output contactor is open) to the magnet windings (when the output contactor is closed). The output contactors have both capacitors across the contacts and reversed diodes on the load side for suppression of the arcs created by opening the contactors at

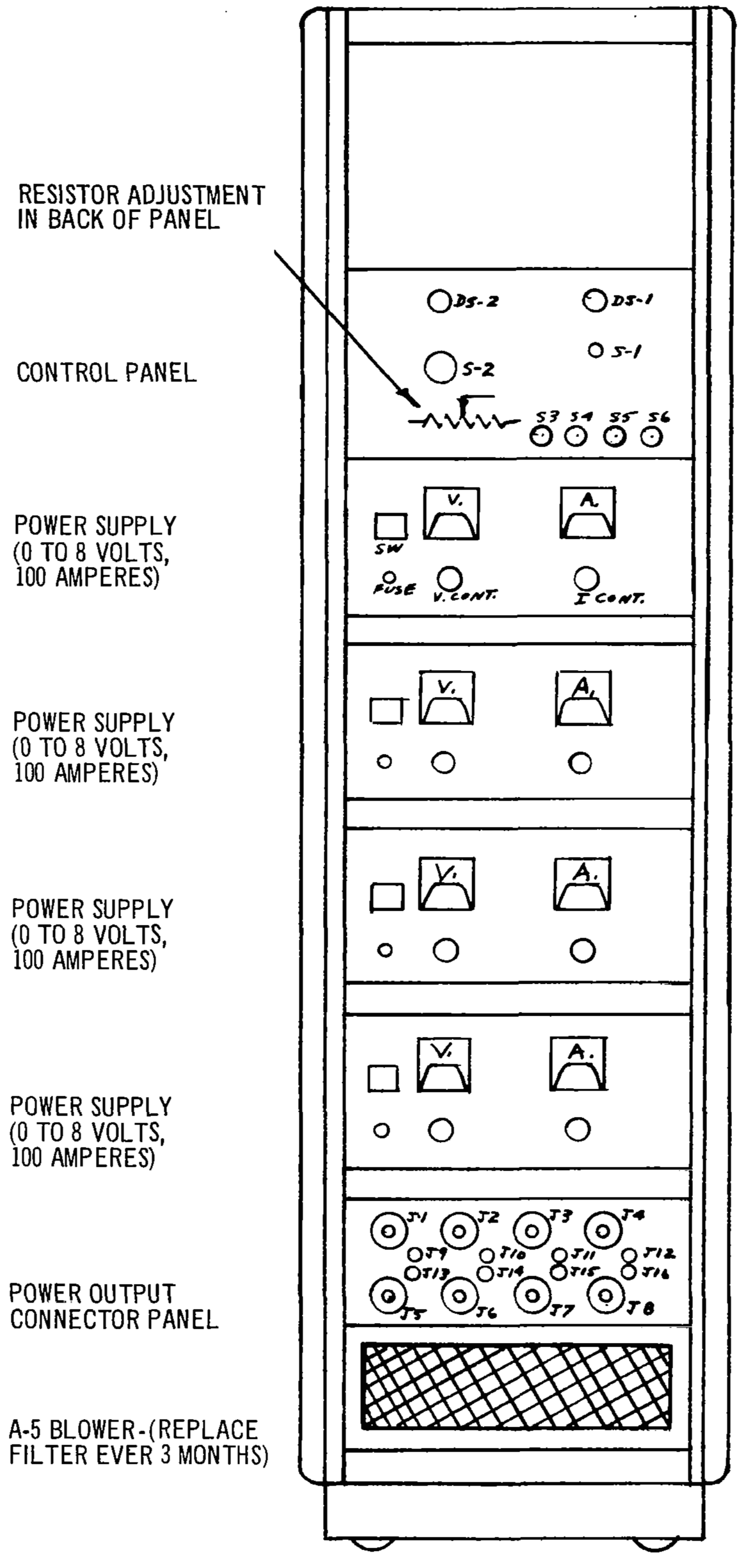


Figure 23. Power Supply Cabinet

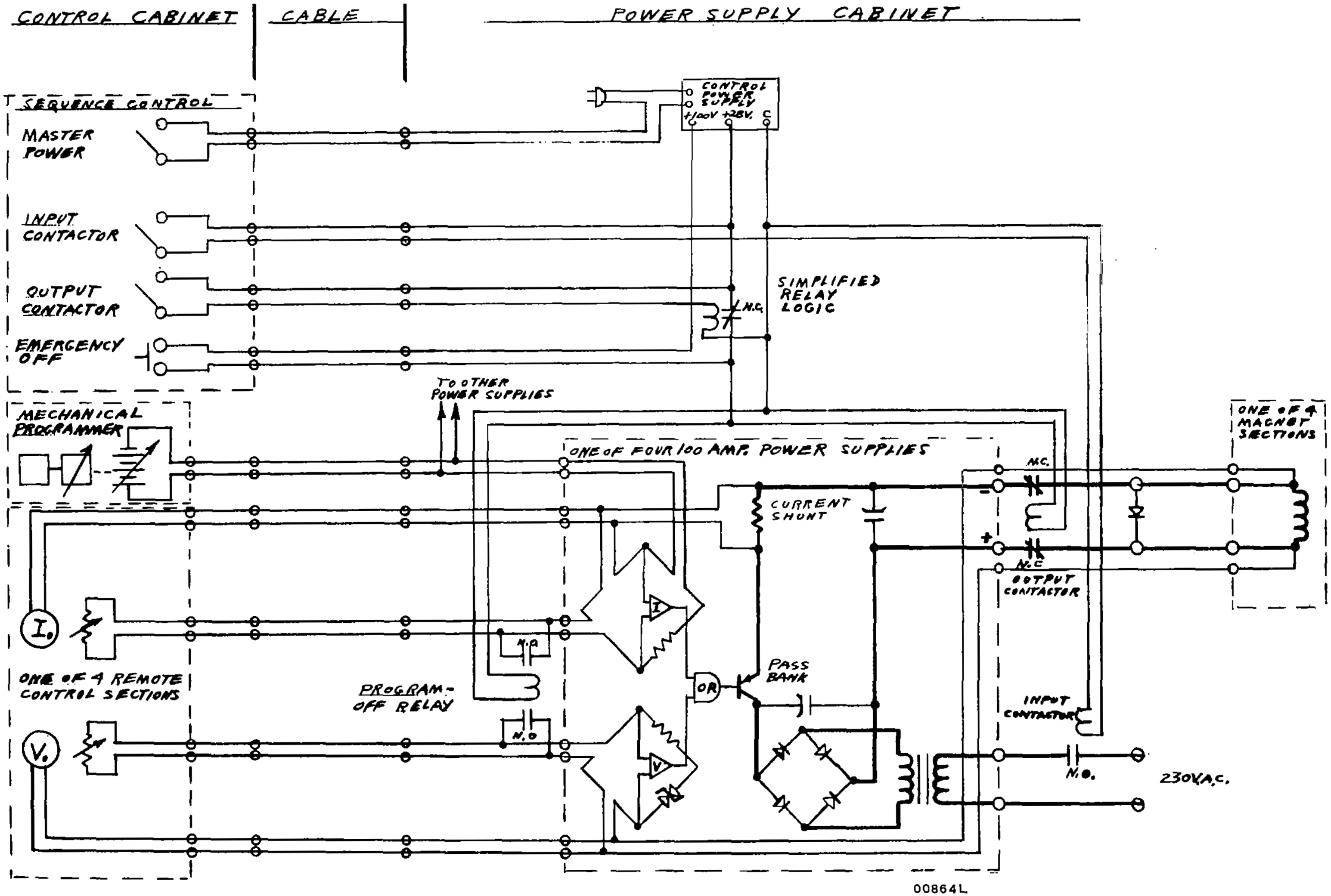


Figure 24. Power Supply Cabinet, Simplified Schematic

high current. The sequence of operation is constrained to require closing the input contactors for checkout of power supply performance before the output contactors are closed for subsequent operation.

Emergency turnoff of the system, which can be initiated either at the power supply cabinet or at the control cabinet, takes advantage of the inherent high speed of mercury-wetted, bistable relays to terminate the introduction of energy into the magnet. This consideration provides the following effects:

a. Both current bridge and voltage bridge of each power supply are programmed to zero

b. A few milliseconds later, the output contactors open, having been overvoltaged by about 400 percent

c. The input contactor opens, returning the control sequence to its starting point.

The power supply cabinet can be operated locally, including both overall sequence control and individual power supply adjustment, by replacing the cable plugs from the control cabinet with a special set of dummy plugs attached permanently to the cabinet. Under this condition, the four power supplies return to their normal mode of operation, with all normal possibilities of separate or combined operation. (Refer to the manufacturer's manual.) To interconnect the remote control cabinet with the power supply cabinet, a two-part cable, containing 15 twisted pairs and 19 shielded pairs, is provided.

C. CONTROL CABINET (FIGURE 25)

The control cabinet contains the components for remote control of the power supplies. The control cabinet also contains a patch panel termination of all magnet diagnositics signal leads in the form of barrier strips. Direct indications of signals that are most important to the operation of the magnet are provided, as well as remote indication of the level of liquid helium in the Dewar. The control cabinet front panel is divided functionally as follows: power supply sequencing, control, and programming; magnet diagnostics signal indications; and Dewar liquid-helium level indication. Switches also are included for operation of control heaters in superconductive "switches," which

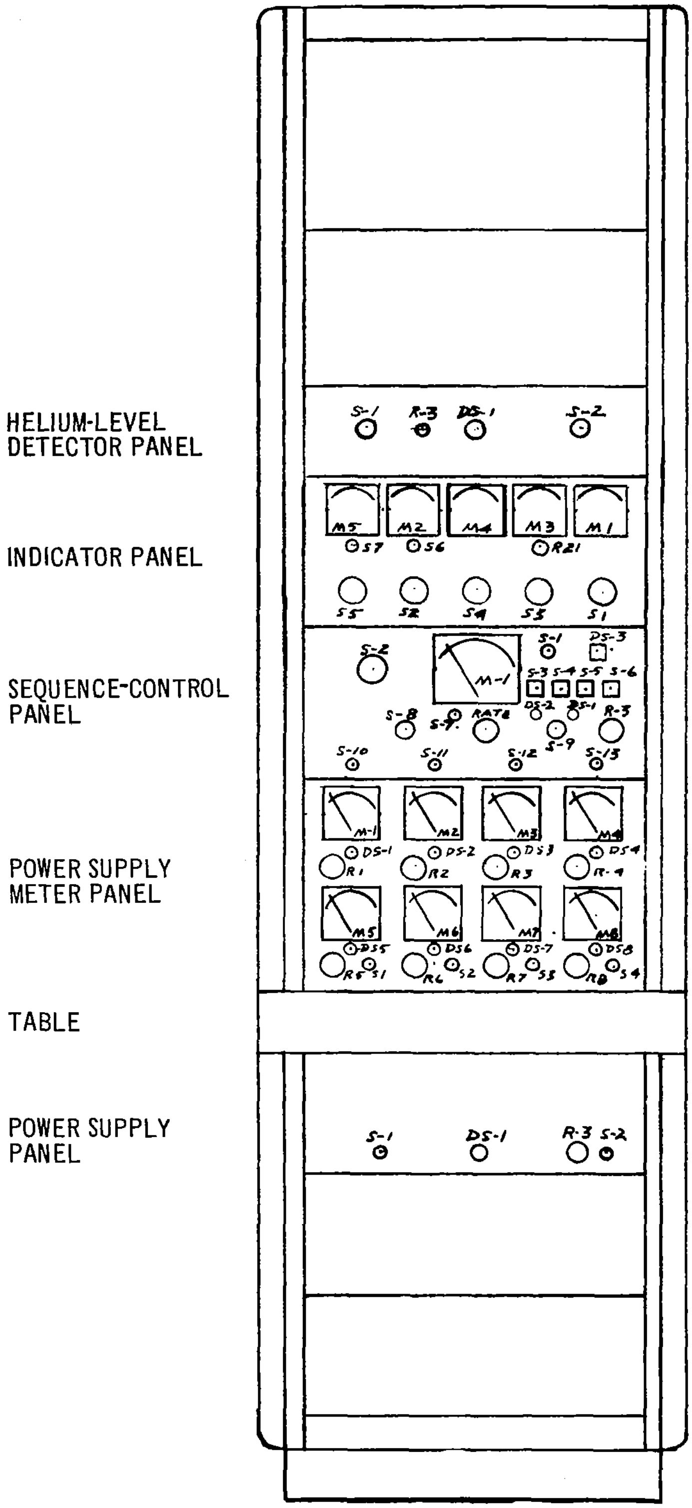


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Figure 25. Control Cabinet

may be added to the system at a later date to permit semipersistent operation of the magnet.

The panel just above the work table of the control cabinet contains multiturn rheostats with turns indicators, each of which forms one leg of the power supply current-control and voltage-control bridges. Current and voltage limits of each remote power supply are adjustable and resetable with precision at the control location. An associated meter is located above each rheostat, and mode lamps indicate which power supply control bridge is in command. Since voltages associated with energizing the magnet usually are small, a pushbutton to effect a X10 increase in sensitivity is connected to each zero-center-scale voltmeter.

The sequence-control panel is immediately above the power supply meter panel. The sequence-control panel contains switches for remote control of the sequence logic circuit in the power supply cabinet. This panel also contains controls for the programmer, a low-level warning light for liquid helium in the Dewar, heater switches for future superconductive "switches," and, for convenience, a large meter that provides an indication proportional to the field in the centroid of the magnet. This panel is the focal point for remote operation of the magnet.

Sequence controls include the master power switch for the logic circuit in the power supply cabinet, individual lighted pushbuttons to open and close both input and output contactors, and the large, red mushroom switch for high-speed emergency turnoff. The remote control logic is arranged to be fail-safe for almost any fault in the cable that connects the control cabinet to the power supply cabinet (e.g., power supplies energizing the magnet will be turned off if the cable is severed or inadvertently disconnected or if individual control wires are shorted to ground or to one another).

The programmer consists of two synchronous clock-type motors, which rotate in opposite directions, connected to a precision, variable-ratio gear with turns-counter control. The variable-ratio gear drives a fixed-ratio reduction gear, the output of which goes through a slip clutch to the programming rheostat-turns indicator shaft. A two-position, center-off switch controls the motors.

Since the speed reduction is in the order of 100:1, turning the motors on and off does not introduce noticable transient to the program. The program can be started, stopped, or reversed at will, and the slip-clutch permits manual changes in the program, such as resetting to zero. The program is continuously variable, from less than 5 percent per hour to about 80 percent per hour (i.e., a linear program of from 1-¼ hours to 20 hours).

The film-type rheostat programs accurately the output voltage of a highly stable power supply (0 to 7 volts, 1 ampere). This power supply provides the reference to the current-control bridges of each of the four 100-ampere magnet-energizing power supplies. The actual current output of each power supply in the program mode is the "percent of program" (indicated by the turns counter on the program rheostat shaft) times the current limit set for that particular supply on the panel below. The four power supplies, therefore, can be set for different ultimate current limits, and they will be programmed at the same percent per hour (but different amperes per hour), so that all power supply currents reach the required limit at the same time. The reference for the current-control bridges of each 100-ampere power supply in the manual mode is set at 100 percent; therefore, the current-limit controls, in this case, indicate directly. Manual mode normally is used for programming the charge-up of the magnet by constant voltage drop at the remote sensing points. In this case, the desired energizing rate is controlled by setting the L(dI/dt) voltage for each section at the power supply remote voltage rheostat; maximum current for each section is set by the current-limit rheostat. (This same type of programming could be done with the mode switch in "program," but then the turns counter on the current-limit rheostat would not read directly.)

The panel above the sequence-control panel is the diagnostics panel. On the chassis behind this panel, all magnet signal leads terminate in barrier strips to which external recording equipment may be attached. The most significant of these signals also may be selected by using the patch cords. The patch cords are attached to selector switches associated with each of five meters on the face of the diagnostics panel. The first meter monitors the voltage drops across 22 modules or across combinations of electrically adjacent modules from the 30 electrical modules of the magnet. Since these voltages normally are quite low, this zero-center-scale, 500-millivolt meter is equipped with a X10 increased-sensitivity pushbutton. The next meter is connected to temperature-sensing carbon resistors buried in four strategic locations within the magnet and is connected to bridge circuits that give a highly nonlinear output (viz, room temperature (300°K) (orange dot) to liquid-nitrogen temperature (77°K) (green dot) is only about one-tenth of the meter scale; but the rest of the scale is devoted to the range from liquid-nitrogen temperature (77°K) down to liquid-helium temperature (4.2°K) (blue dot)). The final stages of magnet cool-down, therefore, as well as heating effects caused by magnet normalcies, may be monitored. For the earliest stages of magnet cool-down, an Ni temperature transducer is included. This transducer has good sensitivity above about 20°K, but it has to be read-out by external means since it obeys a different curve.

There is a noninductive winding of highly pure copper wire on each of the 22 physical modules of the magnet. This winding, which acts as a magnetoresistive probe for the local magnetic field, is approximately linear above a few tens of kilogauss. The two magnetoresistive windings closest to the midplane of the magnet are connected in series to give an integrated signal proportional to the field in the center of the magnet. This signal is read-out on the large meter in the center of the sequence panel. A single constant-current power supply provides control current for these combined probes and for one of the remaining 20 probe windings that is selected by the switch associated with the small-field meter in the center of the diagnostics panel.

The next adjacent meter indicates the output from a high-gain amplifier connected to one of six 1-millihenry, air-core, inductive pickup coils that are situated at various attitudes around the perimeter or to a large, multiturn coil in the bore of the magnet. Changes in magnetic flux density (e.g., "flux jumps") theoretically can be monitorable on this meter; in actual practice, however, operation of the magnet was so quiet (partially as a result of all the copper secondaries) that few signals of this sort were noticed. The $d\phi/dt$ voltage signal from the large inductive coil in the bore on the midplane, however, provides a convenient way to monitor the rate of field increase during energization of the magnet.

The final meter on the diagnostics panel is a general-purpose indicator. It is supplied for possible use with a special external amplifier and/or signal processors to read strain gauges, or to read field, flux, or voltage signals from particular modules that may be of special interest.

The top panel in the control cabinet is the remote indicator for liquid-helium level in the Dewar. A standard technique was adapted to detect, with a simple circuit, the liquid level when the vapors just above the surface are at nearly the same temperature as the liquid (e.g., rapid boil-off during fast transfer). A study of resistance-versus-power dissipation was made for standard 1/10-watt, 100-ohm Allen Bradley resistors under such conditions, and it was determined that a control current of about 20 milliamperes is necessary to differentiate between the heat capacities of liquid and gaseous helium at about $4.2^{o}K$. At only a few milliamperes above this level for most of the resistors tested, there was a dip in the resistance-versus-current curve that would reduce the sensitivity if operation were attempted in this current region. The 20-milliampere control current, therefore, was found to be an optimum level for use with a simple bridge circuit to control the firing of an SCR without the necessity of an amplifier of any sort. Indicator lamps are operated by the SCR, and an audible alarm of some kind may be added.

SECTION V
TEST RESULTS

This section contains a summary of test results for the 15-cm-bore magnet. Extensive recordings and data points giving much more detail are retained at the NASA Lewis Research Center; however, essential characteristics of the tests follow.

The major test problem, as with even smaller multisection coils, was the determination of which section was the first to go normal. The relatively long time constant of the magnet and the large amount of liquid helium used precluded statistical methods of seeking an optimum set of conditions. After a series of initial tests, in which familiarization of magnet and power system was achieved, the testing method used was to test separately and methodically each of the four powered sections to assess reasonable operating currents. The design field of 140 kilogauss was reached during this series of tests, and further magnet testing was not necessary.

Table IV contains summary test data. The first systems check, performed at RCA, Harrison, New Jersey, was conducted according to the original plan of ramping simultaneously all four powered sections to predetermined current levels. Normalcy occurred before full-current levels were reached, but it was impossible to determine which module triggered the normalcy.

In tests I-B and II-B at the Lewis Research Center, normalcies were forced by a combination of excitation of internal heaters in the windings and sudden increases in magnet current. By arranging for the normalcy to occur within a relatively short time period, the viscorder traces were recorded at a high chart speed, and the record of the voltage across each module spread out in time.

The data from test II-B were reduced and plotted as module voltage versus time during normalcy (Figure 26). A quarter-sectional view of the magnet

TABLE IV. SUMMARY TEST DATA FOR 15-CM-BORE, 14-TESLA MAGNET

Test		Max Field[1] (Tesla (kG))	Time (Hours)	Current (Amperes)			
Location	Date			Section I	Section II	Section III	Section IV
Harrison, New Jersey	1-21-67	10.35 (103.5)	15	32.5	41	50	54
Lewis Research Center:							
I-B	3-21-67	5 (50)	7-¼	29[2]	30[2]	25[2]	25[2]
II-B	3-22-67	9.7 (97)	8	43[2]	44.5[2]	42.5[2]	41.8[2]
III	3-23/24-67	10.9 (109)	10-¼	53[2]	(all sections in series)		
IV-B	3-28-67	7.3 (73)	3-½	(---------44.5[2]---------)			31[2]
V	3-28/29-67	10.3 (103)	10	(---------51.0------------)			42
VI	3-29-67	10.2 (102)	8-½	(---44.5[2,3]---)		66.3	44.5[2,3]
VII	4-4-67	10 (100)	10-½	(---------19--------------)			59.5[2]
VIII	4-6/7-67	13.5 (135)	17-½	(----53.5[2]----)		69.2[2]	58
IX - XI	4-25/29-67	10 (100)	13-½ (to 100 kG) 62 (at 100 kG) ~8 (back to 0) ~83-½ total	(-------------------42.2[4]-----------)			

NOTES:

1. Field values determined by MR probe supplied and calibrated by Lewis Research Center.
2. Current being increased at time of normalcy.
3. Sections connected in series; also indicated by (-----).
4. Current for constant 100 kG.

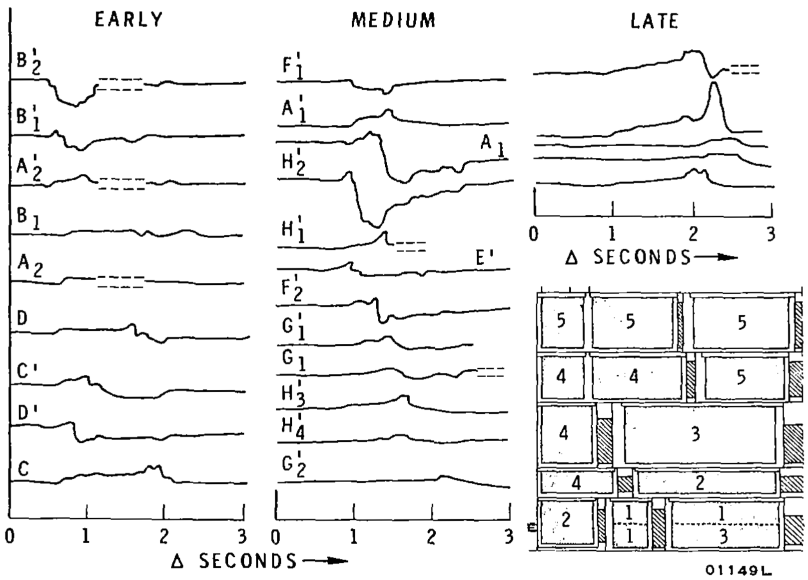

Figure 26. Forced Normalcy Record: Module Voltages and Sequence of Propagation

windings, lower right in Figure 26, shows the relative positions of the modules. The numbers in the module blocks indicate the approximate sequence of propagation, as estimated from the order of occurrence of the first major purturbation of each voltage signal. The varied shapes of these curves indicate a very complex interchange of energy between parts of the magnet, without any particular pattern. Experience with other tests has shown that voltage patterns, even within one module, would be different in overall shape. The sequence of main deviations of voltage, however, shows plainly that the normalcy moves out from modules B and B', which are in the inner row. A later test of a similar nature resulted in approximately the same sequence. Decay of the magnetic field took approximately 8 seconds after the normalcy began.

Test III was run to determine the field attainable under the simplest conditions when all modules are in series. The circuit was changed at the Dewar top by series connection of the four module sections. This approach resulted in some slight lead resistance between the four module sections with perhaps some small amount of resistance decoupling. This resistance is insignificant (i.e., making the series connections at the magnet terminal block would not change the results). Test IV yielded 109 kilogauss at 53 amperes.

Normalcy occurred in test IV-B because of the too-rapid change in currents. For simplicity, only two power supplies were used in test IV-B and test V. This approach was used in an attempt to increase the field value from the 109 kilogauss obtained with all sections in series with one power supply. These tests, however, did not yield definite results.

At this point, it was decided to limit the current in section III of the magnet because of occasional erratic voltage signals from one of the modules in this section. In test VI, section III was held at 66 amperes while the remainder of the magnet was increased to normalcy. This technique did not make a significant difference in the results, adding to what appeared to be a general clustering of fields just above the 100-kilogauss level.

Individual sections were tested methodically, starting at the outermost largest magnet section. In test VII, the inner three sections were set at a low stable current that was just large enough to assume reduced shielding effects so that field from the outer section could more easily penetrate to the bore. This test showed normalcy at 59.5 amperes, which was lower than the current originally designed for this section (72 amperes).

In test VIII, the outer section was programmed to be at a current level lower than 59.5 amperes, and the inner sections were brought up to normalcy using two power supplies. This test was begun as a check on the critical current of section II and I together, but section III also was increasing at normalcy. Test VIII yielded a centroid field of 13.5 Tesla and over 14.0 Tesla on the central plane.

Tests IX, X, and XI were runs by Lewis Research Center personnel for other research purposes. These tests were magnet tests only to establish the long continuous time (62 hours) of operation during which several severe perturbations did not drive the magnet normal.

The magnet system essentially meets the requirements of the original specifications and represents a significant increase in the state-of-the-art of superconductive-magnet technology.

SECTION VI
CONCLUSIONS

The objective design field of 14 Teslas in a 15-cm-bore magnet has been attained. System design was based upon the state of the art in 1965, which involved only the known capabilities for fabricating small magnets (10-Tesla field, 1-inch bore). The feasibility of extrapolating 1965 state-of-the-art data, therefore, with due considerations to additional field and strength requirements, has been established. The modular configuration, which can be considered as an assembly of smaller magnets to make a large magnet, permits direct application of cooling and winding concepts used in smaller high-field magnets.

The one significant area in which design objectives were not attained fully is the time required to bring the magnet to full field. The magnet delivered on this contract requires approximately three times the specified value. The excessive time is the result of using copper shorting strips. The copper shorting strips, which can be considered as conductors in parallel with the high-inductance winding, cause high dissipative currents within the magnet. This property of shorting strips that adds to magnet stability and efficiency of energy dissipation on normalcy therefore also acts to limit the rate at which windings can be brought up to field.

Earlier concern with the need to remove energy from the magnet, by rapid detection of normalcy and fast-acting circuits to dump the energy externally, proved to be unfounded. The problem of providing power to the system, therefore, was simplified to provide several modes of operation as well as to provide diagnostic signals. Most of the diagnostic signals are unnecessary because of the simple and quiet response to commands by the magnet. It is concluded, therefore, that increasing the size and stored energy of superconductive magnets does not mean, necessarily, that the power system must be made correspondingly complex.

One important area of data, which was lacking at the time of initial design, was the degree of critical current degradation that could be expected in very large magnets. While currents required for the initial design were not attained exactly (72 amperes in low-field region to 30 amperes in high-field region), currents achieved during the 14-Tesla tests showed the following condition: currents in one section compensated for currents in another section such that the overall design objective was attained. While specific values of current reduction from short-sample values were not fully predictable, the overall effective current level was as predicted and expected. The design of very large superconductive magnets, which are quasi-stable, therefore, should be flexible to permit variations in current among sections. An important conclusion is that magnets designed in accordance with the approach used for this contract can be quite stable, and the initial concern over excessive current degradation is unfounded. It has been shown also that large-volume, high-field magnets with large values of stored energy can be designed to go from the superconductive state to the normal state repeatedly in a controlled and safe manner.

SECTION VII

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